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WOOD AND OTHER RENEWABLE RESOURCES

Combined application of LCA and eco-design for the sustainable production of wood boxes for wine bottles storage

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Abstract
Methods The main objective of this study is to combine the environmental evaluation of a basic wood box used to store wine bottles by means of the integration of two environmental methodologies: a quantitative methodology known as life cycle assessment (LCA) and a qualitative methodology which is useful in integrating environmental aspects into design, that is, the design for the environment (DfE). The LCA study covers the life cycle of wood box production from a cradle-to-gate perspective. A wood processing company located in Galicia (NW, Spain) was analysed in detail, dividing the process chain into five stages: cogeneration unit, material assembling, painting, packaging and distribution to clients.
Results Abiotic depletion (AD), acidification, eutrophication, global warming, ozone layer depletion (OD), photochemical oxidant formation (PO), human toxicity (HT) and toxicological impact categories (HT, fresh water aquatic ecotoxicity, marine aquatic ecotoxicity and terrestrial ecotoxicity) were the impact categories analysed in the LCA study. According to the environmental results, the assembling stage contributed more than 57% to all impact categories, followed by the cogeneration unit and packaging. Contributions from packaging are mainly due to transoceanic transport activities related to the rope distribution and wood-based materials production. In addition, it is interesting to remark that all energy requirements were produced by on-site cogeneration boilers using a non-renewable fossil fuel. Several processes were identified as hot spots in this study: medium density fibreboards (MDF) production (with large contribution to ecotoxicity categories), energy production (with contributions to AD, GW and OD) and finally, the transportation of jute fibres (the main contributor to all the impact categories). Concerning the results from the DfE, the proposed eco-design strategies were evaluated from a technological, economic and social point of view by an interdisciplinary team of researchers and enterprise's workers. The results show that the strategies with more viability of improvement were: reduction of resources used, multifunctional design, substitution of MDF by plywood, substitution of jute fibres, alternatives to the ink, optimization of energy requirement, transport alternatives for the final product and inputs distribution and definition of a protocol for disassembling the product.

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Conclusions The results obtained in this work allow forecasting the importance of the chosen raw materials as well as their origin for the environmental burdens associated with the wood-based box manufacture. Future work will focus on the manufacturing of a prototype eco-designed wood-based box.

Keywords Design for environment · Eco-design · Environmental performance · Wine sector · Life cycle assessment (LCA) · Wood box · Wood sector

1 Background, aim and scope

The European Union (EU) is one of the largest producers, traders and consumers of wood products in the world (European Commission 2010). Wood sector (forestry, forest-based and related industries) comprises the following industrial subsectors: (1) woodworking, (2) cork and other forest-based materials, (3) pulp, paper and paper-board manufacturing, (4) paper and paper-board converting and (5) printing industries. Specifically, wood processing involves the conversion of trees into useful consumer products and/or building materials such as wood boards. The woodworking industries supply basic products such as sawn goods, wood panels and builders' carpentry for construction, internal decoration and packaging (pallets and boxes) (European Commission 2010).

Assessments of the environmental impacts of wood-based products have traditionally focused on energy consumption in the production processes (Boyd et al. 1976; Ressel 1986). Nowadays, there is a growing interest in procurement of wood-based goods produced in a sustainable manner. Concerned consumers, retailers, governments and other groups are increasingly demanding positive social and environmental contributions in the retail process. Sustainable development is a major concern in developed countries, resulting in stricter regulations concerning the impact of products during their manufacturing, use and end of life, including compulsory definition of reverse logistic strategies and systems.

Life Cycle Assessment (LCA) methodology is a suitable and valuable tool to assess the environmental impact of materials, products and service systems and should be part of the decision-making process towards sustainability (Baumann and Tillman 2004). Several studies have recently been carried out in relation to the production of wood-based products such as wood floor coverings (Nebel et al. 2006; Petersen and Solberg 2003), particleboards (Rivela et al. 2006), MDF (Rivela et al. 2007), hardboards (González-García et al. 2009) and related wood items such as window frames (Asif et al. 2002; Richter and Gugerli 1996), walls (Werner 2001) and furniture (Taylor and van Langenberg 2003). Wood is also an important primary material for other products and activities such as paper production and packaging sector (Gasol et al. 2008).

In this sense, the production of wood semi-trailer load boxes for grain transport have also been analysed from a LCA perspective (Echevenguá Teixeira et al. 2010). Recent studies have demonstrated that wood products properly installed and used tend to have a more favourable environmental profile compared with equivalent products from other materials (Werner and Richter 2007). In addition, social aspects related to the forest sector have also been analysed (Puy et al. 2007)

On the other hand, one of the most valid tools to reduce the inherent environmental burdens associated to products is eco-design or design for the environment (DfE). This methodology consists of applying environmental criteria to the development of a product and means a change in how we look at these products. Examples vary from the automobile sector (Muñoz et al. 2006), leather tanning industry (Rivela et al. 2004), packaging and packing (Bovea and Gallardo 2006) to waste management (Todd et al. 2003). The interdisciplinary team which works on the environmental aspects in such design is key for the improvement of product stages: productive materials, process, transport, packing, installation, use, maintenance, dismantling and end of life, as they are aware that these initial decisions have a consequence on the whole life cycle (Borsboom 1991; Brezet and van Hemel 1997). This change in the design process translates into a new vision for the reduction of environmental emissions: a vision of final treatment, consisting of the management of the waste generated in the dismantling of the product, a vision of environmental improvement of the whole life cycle (McDonough et al. 2003; Zust and Wimmer 2004), which takes all the stages involved into account.

In this study, we focused on the environmental evaluation of the manufacture process of wood boxes. This type of product is a container made of wood for storage or as a shipping container. The construction may include several types of wood, timber, plywood, engineered woods etc., and for some purposes, decorative woods are used. Wood-based boxes are often used for packaging when mechanical resistance is needed for heavy and difficult loads, long-term warehousing or adequate rigidity. Specifically, wood-based boxes are commonly used in food sector to store bottles, nougat candy, fish or fruit and their production process must fulfil several requisites such as a fitosanitary thermal treatment (NIMF-15 2009). Until now, no LCA and DfE studies are available for wood box production as storage of not only wine bottles but also other utensils. The objective of this paper is to analyse the industrial process of wood box manufacture by using the combined application of LCA and DfE as well as to compare its environmental

profile with potential alternative scenarios. The eco-design of a wood-based box is a challenge at the environmental improvement of a wood product which is used at a global level.

2 Goal and scope definition

2.1 Objectives

This work aimed to environmentally analyse the manufacture of a wood-based box commonly used for the storage of wine bottles. Three objectives are identified: (1) the LCA study to detect the environmental 'hot spots' of the wood box throughout the production life cycle as well as to propose improvement actions for these hot spots, (2) the reduction of its environmental impact by means of the practical adaptation of the methodology of eco-design in its development and finally and (3) the development of the concept of eco-briefing as a communication tool to facilitate an understanding of environmental factors to designers and other enterprise's technicians not familiar with DfE.

A Spanish company, located in Galicia (Northwest Spain), considered representative of the state of the art, was selected to study the process in detail. This company is the largest Spanish producer of wood panels such as chipboard and medium density fibreboard (MDF) and produces a wide and varied range of panel products (veneers, plywood, wine racks, platforms, boxes and laminated flooring), printed and impregnated paper as well as chemicals (formaldehyde and glues). The assessment of a wood box was carried out as this product has a good market and similarity with other products so the environmental solutions reached in this study could be applied to other wood products. The study covers the whole life cycle of a wood box manufacturing from the production of raw materials to its delivery to the wine sector.

2.2 Functional unit

The functional unit selected corresponds to one wood box (1.35 kg) for the storage of three standard wine bottles with the following dimensions: 350×260×103 mm. The box is made with a structure of solid pine timber and MDF and a handle of jute rope. Fig. 1 illustrates the wood-based box under study.

2.3 Description of the system under study

Wood boxes are panel products commonly used in sectors such as food sector (beverage, fish and fruit), do-it-yourself sector, construction sector, gardening and packaging. In this study, we have paid attention of wood boxes used for wine bottles storage. This product mainly consists of wood-based panels such as MDF or plywood joined with metal pieces such as brads, hoops and staples. There are several dimensions depending on the number of bottles stored (one, two, three, six and/or 12). In this paper, the production of a box for three bottles was considered as it represents the item with the highest production in the factory under study. Additionally, a large number of enterprises in the wine sector worldwide use the same box format.

Fig. 1 Product under assessment: wood-based box to storage three wine bottles

The process chain was divided into five stages: the cogeneration unit, the assembling stage, the painting stage, the packaging stage and the distribution to clients. Ancillary activities such as production and transport of chemicals, boards, metal pieces or packaging materials were also taken into account and computed within the system boundaries. The inventory data came from interviews, surveys and on-site measurements. The system investigated is illustrated in Fig. 2.

A mass balance analysis was performed for the production of a wood-based box. The production line consists on the production and reception of wood materials for the structure (solid pine timber and MDF) as well as the reception of remaining materials (metal pieces, ink, jute rope for the handle and packaging materials). Thereafter, the wood-based boards are cut according to the dimensions of the box and assembled. The next step is the painting of the box and packaging to be later distributed to final users. It was not possible to separate energy use among the production stages, therefore, the cogeneration unit was assumed as another step.

2.4 Data quality and simplifications

The most effort consuming step in the execution of LCA studies is the collection of inventory data in order to build

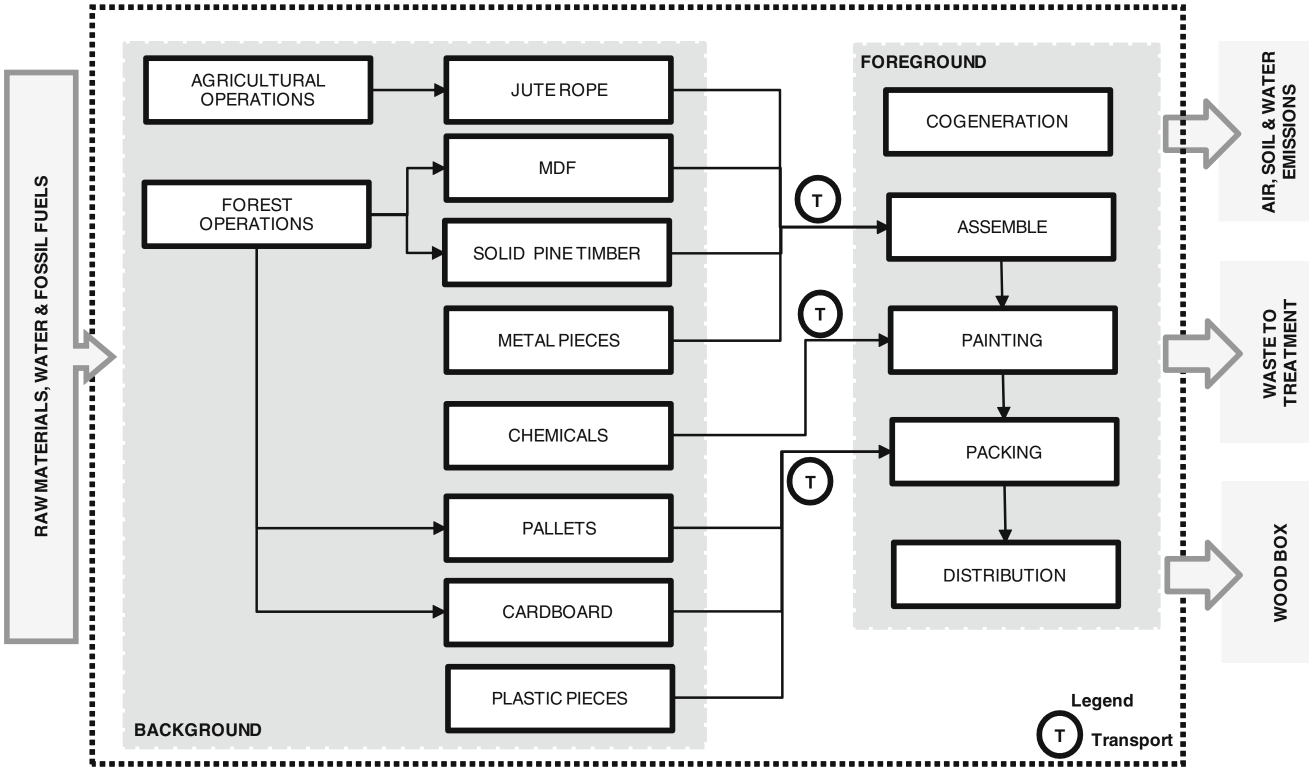

Fig. 2 System boundaries and process chain under study

the life cycle inventory (LCI). Moreover, high quality data are essential to make a reliable evaluation. Data for the study was collected from different sources. The inventory data for the foreground system (box manufacturing process) consisted of average annual data obtained by on-site measurements in the mill. Whenever possible and viable, typical process-specific data were collected to avoid anomalous conditions.

Other inventory data for the background system (such as chemicals production) were obtained from databases (Table 1). Inventory data for metal pieces production such as staples, brads and hoops were taken from the IDEMAT Database (2001). Inventory data for the plastic pieces production such as hoops and film, the production of alkyd paint, jute rope based handle, solid timber and wood pallets were taken from the Ecoinvent database (Hischier 2007; Althaus et al. 2007a; Althaus et al. 2007b; Werner et al. 2007; Kellenberger et al. 2007).

The main raw material for the box is MDF and solid pine timber. The inventory data for MDF production were taken from a previous research study (Rivela et al. 2007) where three factories, considered representative of the 'state of the art', were selected to study the production process in detail.

In the mill under study, all energy requirements are produced in a cogeneration unit where only fossil fuel with low sulphur content is burnt. Concerning waste generation, rejects from solid timbers are re-used in the mill. Other waste from the packaging such as plastic hoops, PE film and corrugated board are picked up and sent to treatment. The treatment and distribution of these wastes were excluded from the system boundaries.

When setting LCA boundaries, it must be decided whether the production and maintenance of capital goods is included within the system boundaries. In this study, it was excluded from the analysis since it was assumed to be comparable to that of plants producing functionally similar materials (Jungmeier et al. 2002). Besides, several industrial LCA studies have shown that the environmental load from the production of capital goods is insignificant when compared with their operation stage (Rivela et al. 2006; Rivela et al. 2007). The inventory table of the global process is shown in Table 2 and extra data sources are summarised in Table 1.

2.5 Allocation procedure

Allocation (partitioning of input or output flows of a unit process to the product under study) is one of the most critical issues in life cycle assessment (ISO 14044 2006). A feature of this wood-based industry is the simultaneous production of diverse products. In this factory, several products are manufactured (panels, boxes, papers etc.); therefore, an allocation procedure was necessary in order to allocate the environmental burdens among the different

Table 1 Global inventory for one wood-based box (350×260×103 mm)

Energy	Electricity	Ecoinvent database (Dones et al. 2007) and FINSA (personal communication)
Transport	Truck, van and transoceanic tanker	Ecoinvent database (Spielmann et al. 2007)
Chemicals	Ink	Ecoinvent database (Althaus et al. 2007a)
Structure	Solid pine timber	Ecoinvent database (Werner et al. 2007)
	MDF	Rivela et al. (2007)
	Metal pieces (brads, hoops and staples)	IDEMAT (2001)
	Handle (jute rope)	Ecoinvent database (Althaus et al. 2007b)
Packaging	Corrugated cardboard	Ecoinvent database (Hischier 2007)
	Wood pallet	Ecoinvent database (Kellenberger et al. 2007)
	Plastic pieces (hoops and films)	Ecoinvent database (Hischier 2007)

products. Each allocation method (mass, economic etc.) has advantages and disadvantages and the choice of the allocation procedure depends on the limitations of the study (ISO 14044 2006; Guinée et al.. 2001). Although economic allocation is not the priority, it was not taken into account since it was not possible to find market prices for all the products produced in the mill. Therefore, mass allocation was assumed in this study, taking into account the annual production.

3 Life cycle assessment for the current wood box production

A retrospective LCA for wood box manufacture was carried out according to the CML 2 baseline 2000 v2.1 biogenic method to quantify the environmental impact (Guinée et al. 2001). This method results in the definition of an environmental profile for the assessed product/process/service by quantifying the environmental effects on different categories, while only indirect or intermediate effects on humans can be assessed. The impact categories analysed in this study were: abiotic depletion (AD), acidification (AC), eutrophication (EP), global warming (GW), ozone layer depletion (OD) and photochemical oxidants formation. In addition, toxicological impact categories (human toxicity, fresh water aquatic ecotoxicity (FE), marine aquatic ecotoxicity (ME) and terrestrial ecotoxicity (TE)) were also analysed although the LCA community has not yet reached a consensus on the characterisation models for their definition (Larsen et al. 2004). The LCA software SimaPro 7.10 developed by PRé

Table 2 Summary of data sources

Materials		Energy	Transport	Waste to treatment	
Inputs from technosphere					
Solid pine timber	1.94 kg	Electricity from cogeneration			0.261 kWh
MDF	$3.45 \cdot 10^{-3}$ m^3				
Jute rope	3.10 g		20–28 t truck		0.615 t·km
Metal staple	4.40 g		Van (<3.5 t)		0.006 t·km
Ink	12 mg		Transoceanic tanker		37.12 t·km
Plastic hoop	6.20 g				
PE film	0.80 g				
Corrugated board	4.60 g				
Pallet	56.30 g				
Metal brad	2.40 g				
Metal hoop	0.03 kg				
Outputs to technosphere					
Wood box	1.35 kg			Plastic hoop	6.20 kg
				PE film	0.80 kg
				Corrugated board	4.60 kg
				Solid pine timber (internal recycling)	0.97 kg

Consultants (PRé Consultants 2008) was used for impact assessment. The results for the characterisation step are shown in Table 3.

Fig. 3 shows the relative contributions of the wood box production process to each impact category taking into account the five production stages. According to these results, the assembling stage is the most important with contributions higher than 60% to all impact categories, followed by the cogeneration unit and packaging stage. This result was due to the fact that the consumption of materials (boards and metal pieces) only takes place in this stage. Furthermore, a more detailed study of each impact category was carried out. Fig. 4 shows the relative contribution of the main processes to each impact category and, in keeping with the results, it is seen that three processes have a contribution of more than 25% to almost all impact categories: wood-based materials production (the main component of the box in terms of weight), the cogeneration unit and the transport of inputs to the mill.

Abiotic depletion potential This impact category is related to extraction of minerals and fossil fuels due to inputs in the system under study. The contributions to this impact category are dominated by the transport (40%), followed by the cogeneration unit (24%) and wood-based materials production (26%). The main substances which contribute to this impact category are fossil fuels such as crude oil (69%) required in the transoceanic transport and as fuel in the boilers in the cogeneration system as well as natural gas (18%) mainly used in the MDF production process.

Acidification potential Transport related activities were the most important contributors to AC (76%) followed by far by the wood materials production (16%) according to Fig. 4. Emissions of SO_2 (74%) and NO_x (24%) from fossil fuels were the main contributing emissions to this impact category.

Table 3 Impact assessment results (characterization step) of one wood-based box (350×260×103 mm)

Impact category	Unit	Value
Abiotic depletion	kg Sb_{eq}	$2.08 \cdot 10^{-3}$
Acidification	kg SO_{2eq}	$5.72 \cdot 10^{-3}$
Eutrophication	kg $PO_4{}^{-3}{}_{eq}$	$5.69 \cdot 10^{-4}$
Global warming	kg CO_{2eq}	$3.14 \cdot 10^{-1}$
Ozone layer depletion	mg CFC-11$_{eq}$	$3.95 \cdot 10^{-8}$
Human toxicity	kg 1,4-DB$_{eq}$	$1.35 \cdot 10^{-1}$
Fresh water aquatic ecotoxicity	kg 1,4-DB$_{eq}$	$7.40 \cdot 10^{-3}$
Marine aquatic ecotoxicity	kg 1,4-DB$_{eq}$	27.3
Terrestrial ecotoxicity	kg 1,4-DB$_{eq}$	$6.05 \cdot 10^{-4}$
Photochemical oxidation	kg C_2H_{2eq}	$2.11 \cdot 10^{-4}$

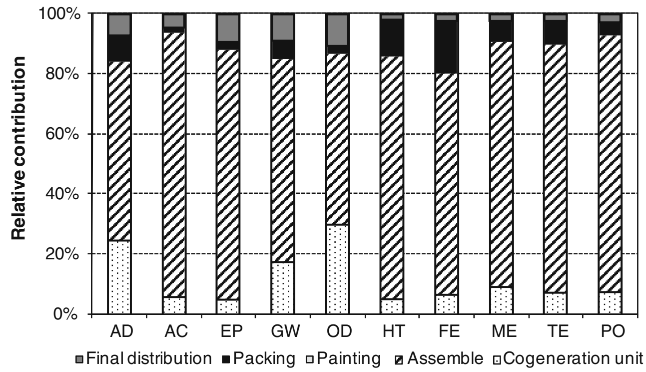

Fig. 3 Relative contributions per stages (in.%) to each impact category. Impact category acronyms: *AD* abiotic depletion, *AC* acidification, *EP* eutrophication, *GW* global warming, *OD* ozone layer depletion, *HT* human toxicity, *FE* freshwater aquatic ecotoxicity, *ME* marine aquatic ecotoxicity, *TE* terrestrial ecotoxicity and *PO* photo-oxidant formation

Eutrophication potential Once again, transport activities and wood-based materials production were the main hot spots with contributions of 70% and 19%, respectively (see Fig. 4). Concerning the contributing emissions, airborne NO_x emissions showed the greatest contribution to EP (~58%), followed by those of COD to the water (~35%) mainly derived from the transoceanic transport of jute fibres.

Global warming potential Once again, the transport of inputs to the mill was responsible for most of the GW contributions (~49%) specifically the distribution of jute rope, which is originally produced in India. The production of wood materials, specifically the MDF and the cogeneration unit were responsible for 26% and 18% of total carbon dioxide equivalent emissions (see Fig. 4). The transoceanic transport of jute fibres accounted for more than 32% of the total contribution. It is important to remark the combustion of fossil fuel in the cogeneration boilers to produce all the energy requirements, which gave rise to fossil CO_2 emissions (~14% of total). The use of biomass could be interesting from an environmental point of view in order to improve its environmental profile. Fossil CO_2 emissions gave the greatest contribution (~93%) to this impact category, followed by CH_4 and N_2O.

Ozone layer depletion potential The main contributor to this impact category was the transport (48%) due to the jute handle transportation. The second largest contributor to OD

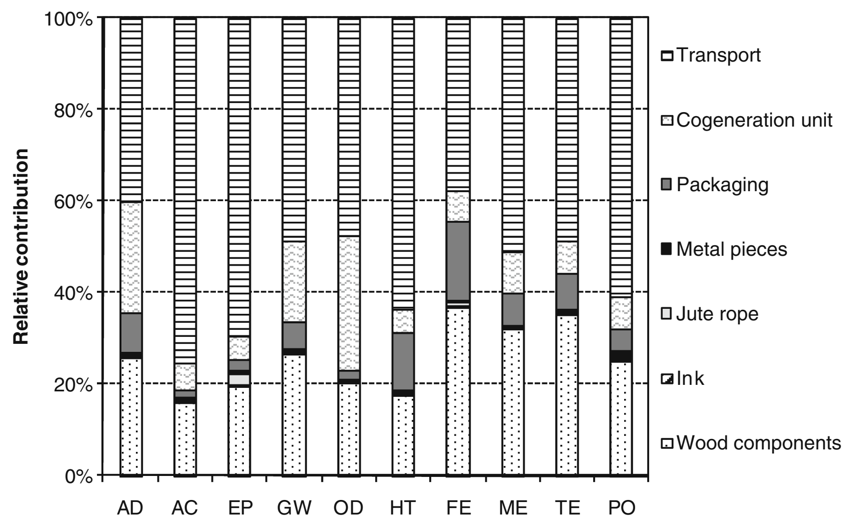

Fig. 4 Relative contributions per processes (in.%) to each impact category. Impact category acronyms: *AD* abiotic depletion, *AC* acidification, *EP* eutrophication, *GW* global warming, *OD* ozone layer depletion, *HT* human toxicity, *FE* freshwater aquatic ecotoxicity, *ME* marine aquatic ecotoxicity, *TE* terrestrial ecotoxicity and *PO* photo-oxidant formation

was the cogeneration unit (30%) and the remaining contributions were mainly related to the production of MDF (16%).

Human toxicity potential Approximately 64% of contributions to this impact category were associated with the transport activities followed by wood-based materials production, mainly MDF, with a much lower contribution (17%). The packaging of finished wood box is another hot spot with contributions of more than 12% specifically due to the production of the pallet (10%) required for the transport of finished product inside the mill. It is important to consider the airborne emissions of polycyclic aromatic hydrocarbons (36%) and nickel (22%) as well as waterborne emissions of benzene (6%).

Ecotoxicity potentials A high percentage of the total impact of ecotoxicity potentials was linked to transport activities (38%, 51% and 49% in FE, ME and TE, respectively) mainly due to the transportation of jute rope. Another important contribution was linked to the wood-based materials production with inputs of more than 32% to each ecotoxicity impact categories. Waterborne emissions, particularly those of vanadium from fossil fuels combustion dominated the contributions to FE (28% of total) and TE (33% of total). Emissions of barium (18%) and barite (17%) also from fossil fuels combustion to water dominated the contributions to ME.

Photochemical oxidants formation potential The transport activities had the largest contribution to the potential impact of photochemical oxidant formation (61%) followed by the wood-based materials production (25%). The PO of the system studied was mainly caused by SO_2 emissions (65%), which were strongly related to energy use.

4 Design for the environment for the current wood box

4.1 Introduction and stages of DfE

The adaptation of a methodology which facilitates the communication of environmental factors among environmental experts and designers employing basic information about the product to be designed and defining the product with the environmental objectives to be achieved is defined as eco-briefing (Smith and Wyatt 2006), Firstly, certain environmental objectives must be set for a proper conceptual development, based on which, and by means of a critical review by a panel of expert participants, the process of eco-design is begun. By establishing these initial criteria, which relate to various stages of the life cycle, we obtain global environmental improvements in the new product.

The adapted methodology consists of the following stages (Fig. 5):

Stage I. The creation of a multidisciplinary eco-design team

The creation of the team which will participate has to cover the fields of knowledge implied in DfE: environment and design. The interdisciplinary team in this study was made up of designers, engineers, environmental scientists, chemists and experts in the field of wood-based products. The formation of a multidisciplinary team has been very positive given that we have managed to link the values of two concurrent disciplines: environmental aspects and the development of product design. We have seen the need to carry out basic environmental training of designers and technicians to facilitate communication with environmental technicians.

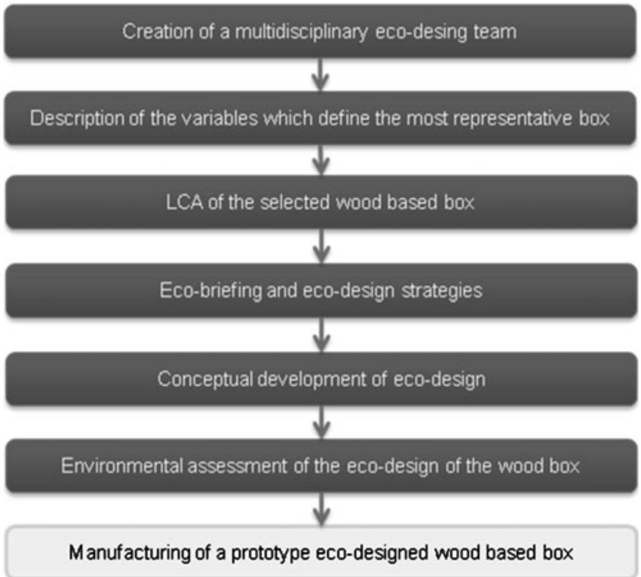

Fig. 5 Stages in the adapted methodology for the eco-design of a wood-based box to storage three wine bottles. *White box* include the stage not considered in this study

Stage II. Describing the variables which define the most representative wood-based boxes

Given the great variety of boxes, the market study implies restricting the typology of boxes to be eco-designed. The boxes under study are defined according to their dimension and application: the boxes will be used to storage wine bottles and with the following dimensions: 350×260×103 mm. To limit the study the following selection criteria were selected: the degree of implementation and representation of the materials in question and degree of complexity. An example of box to storage three wine bottles was taken into account since this is a representative product for the plant, with a high market demand as well as with similarities with other products. Therefore, the solutions achieve for this product can be applied to similar products.

Stage III. A life cycle analysis of the selected wood box

A LCA was undertaken in the previous section, with the aim of determining the critical environmental factors involved in the production process as well as to identify the hot spots (processes with the highest potential environmental impact).

As was mentioned before, the box production process has been analysed in detail and according to our results, the production of one of the main wood components (MDF), the transport of inputs to the mill (specifically transoceanic distribution of jute rope) as well as the production of energy requirement by fossil fuels are the main hot spots and considerably influenced the environmental burdens of the production system (see Figs. 3 and 4).

Stage IV. Eco-briefing and strategies of eco-design

The briefing (Gilbertson 2006) includes environmental aims that should be considered in the development of eco-design. Eco-briefing is the way of communicating to the designers the environmental goals to be achieved by means of DfE as well as it should guide them on the most appropriate eco-design strategies to be applied.

Alternatives that eco-briefing addresses with the aim of improving the current environmental conditions of a product are known as strategies of eco-design (Bhamra 2004; Ferrao and Amaral 2006). Eco-design strategies analyse the technological, social and financial aspects, which will be evaluated by the participating technical team.

The results of the eco-*briefing* indicate that the solutions should be focused on the concept definition, production and distribution (Table 4). The conceptual stage defines the rest of the product stages and it is very important to solve the hot spots through (1) the replacement of the function and performance (technical and aesthetic), (2) the reduction and/or internal recycling of the generated wastes and (3) the promotion of an optimum transport reducing the distribution volume or considering alternative transportation. The correct selection of vehicles

Table 4 Definition of key environmental hot spots and life cycle stages for their solution

Environmental hot spots	Key life cycle stages to their solution				
	C	M	P	D	E
Box functionality	■	□	□	□	□
High energy and water consumption	□	□	■	□	□
High impact vehicles	□	□	□	■	□
Low optimization of transport volume	■	□	□	■	□

C concept, *M* materials, *P* production, *D* distribution, *E* end of life

for transport and the application of more efficient production technologies could be key factors for the achievement of the eco-design and the reduction of its environmental profile. Fig. 6 represents the results from the eco-briefing.

The eco-design strategies were evaluated from a technological, economic and social point of view; the strategies which showed most viability were (Table 5): reduction of resources used, multifunctional design, substitution of MDF by plywood, substitution of jute fibres by others, alternatives to the ink, optimization of energy requirement, transport alternatives for the final product and inputs distribution and definition of a protocol for disassembling the product.

Stage V. Conceptual development of eco-design

Based on the above strategies of eco-design we can define the conceptual line to be followed. We can eco-design the wood-based box taking into account the following aspects: formal, functional, number of bottles, user related and technical, as well as the environmental factors identified earlier. During the development of the eco-design a constant relation among the team members is key to analyse, in situ, the various different lines of work which are being carried out.

Stage V shows how the concept of an eco-wood box can be developed by integrating these eco-design strategies. For this reason, several improvement alternatives have been proposed on these elements or processes and analysed in order to try to reduce the associated environmental burdens taking into account the environmental results from LCA and the eco-design strategies (stage VI). It should be interesting to remark that the opinions of the wood box producers have been taken into account in the definition of these alternative scenarios.

Stage VI. Discussion of the eco-design alternatives and their environmental evaluation

The results from the LCA are compared with those obtained in the eco-briefing. The aim of this comparison is to assess the degree of environmental improvement that is introduced by the eco-designed element.

4.2 Results from DfE

4.2.1 Alternatives focused on the main component: wood-based materials

Wood based material is the main component of the product under study since solid pine timber and MDF represent the 72% and 22% of total weight, respectively. However, the main contributions to the environmental profile are associated to the MDF production instead of solid pine timber specifically due to energy and chemicals requirement to their production. For this reason, it was proposed the substitution of MDF (ScA1, $3.45\cdot10^{-4}$ m^3 of board per box) by pine plywood (ScA2, $2.58\cdot10^{-4}$ m^3) or alternatively,

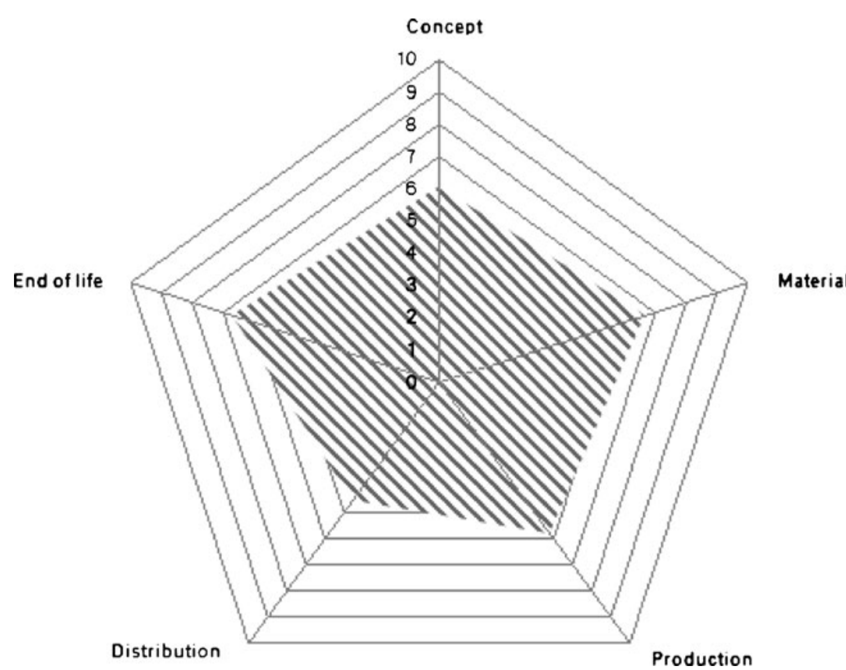

Fig. 6 Graphical representation of the eco-briefing results for the wood-based box under assessment

Table 5 Eco-design strategies, and a viability evaluation in technological, financial and social terms

Stage	Eco-design strategy	Technology	Finance	Social
C	Reduction of resources used	++	++	+
C	Reduction of components number	−	−	−
C	Multifuctional design	++	++	++
C	Design for assembling (and disassembling)	−	−	−
M	Substitution of MDF by plywood	++	+	++
M	Substitution of MDF by pine solid timber	−	−	−
M	Substitution of jute fibres by other fibres (hemp, cotton, synthetic fibres)	++	++	++
M	Reduction in the amount of materials	−	−	−
M	Removal of metallic unions	−	−	−
M	Alternatives to the ink	++	++	++
P	Optimization of energy consumption	++	++	++
D	Transport of final product using biofuels as transport fuel	++	++	++
D	Transport of inputs using biodiesel as transport fuel	++	++	++
D	Optimization of jute fibres transport	++	++	++
D	Reduction of material for packing	=	=	=
G	Protocol of disassembling and use	++	++	++

C concept, *M* material, *P* prduction, *D* distribution, *G* final management, (++) important improvement, (+) slight improvement, (=) no effect, (−) unfeasible

solid pine timber (ScA3, $4.23{\cdot}10^{-4}$ m^3). Fig. 7 shows the comparative environmental profile associated to these alternative scenarios. According to these results, the change from MDF to plywood would lightly reduce the contributions to AD; AC, GW, OD and ME. However, the contributions to almost all ecotoxicity impact categories should be increased (up to 129% in TE) mainly due to the pollutant emissions associated to the plywood production. However, the box weight should be reduced by ~10%. Concerning the use of solid timber instead of MDF, the box weight should be increased by 8% but the environmental profile is improved in all impact categories analysed and reductions of more than 30% can be achieved in categories such as TE, all of them associated to the solid timber production process which requires lower amounts of chemicals and electricity. However, although the solid pine timber substitution favours the environmental profile, it is unfeasible (see Table 5) from technological and design issues point view because the pine board wide is not enough to make the lid of the box in one piece. This drawback does not exist when plywood is proposed.

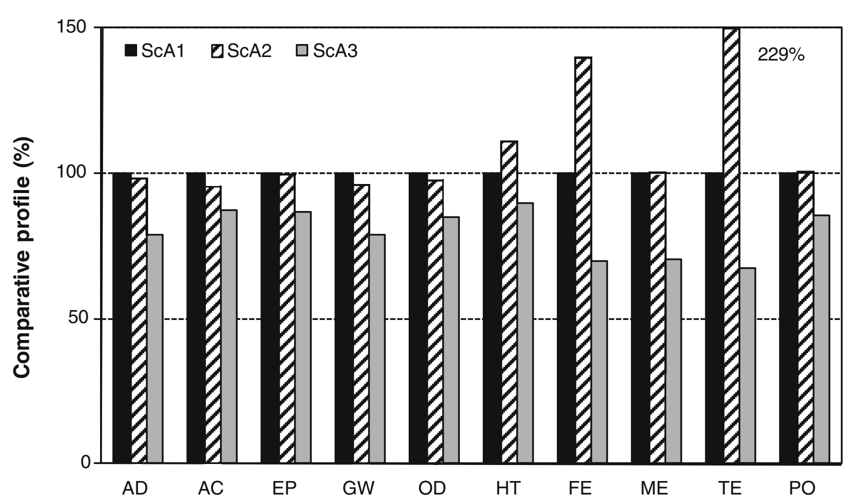

Fig. 7 Relative environmental profile of the different alternative scenarios proposed with regard to wood-based material, the current scenario serving as the baseline (Index=100). Acronyms: *ScA1* current scenario, *ScA2* plywood instead of MDF, *ScA3* solid pine timber instead of MDF

4.2.2 Alternatives focused on the jute rope handle

In this case study, jute rope is used as raw material for the box handle (from now, ScB1). Jute rope is transported from India (one of the main producers of jute fibres in the world). This transportation entails transoceanic transport which represents an important role in the environmental profile with contributions up to 54% and 68% in EP and AP, respectively. For this reason, several alternative fibres with similar characteristics were proposed in order to try to reduce these environmental burdens and to promote the use of fibres cultivated in Spain, which would imply lower transport distances. The alternative fibres proposed were: cotton fibres from Cordoba, South Spain (ScB2), hemp fibres from Lleida, East Spain (ScB3) and finally, synthetic fibres from Madrid, Central Spain (ScB4). According to the results showed in Fig. 8, it is possible to improve the environmental profile in all alternative scenarios. The highest reductions are achieved by the ScB3, where hemp fibres are used as raw material for the handle (influence of the lowest transport distance: ~1,000 km), followed by the use of synthetic fibres (mainly due to the lowest transport distance: 607 km). By contrast, the use of cotton fibres considerably increases the impact to two environmental categories, FE and TE, mainly due to their agricultural stage specifically because of the requirement of large amount of fertilizers and pesticides.

4.2.3 Alternatives focused on the optimization of the energy requirements

An important contributor to the environmental profile in the current scenario (from now, ScC1) is the production of the energy requirements from low sulphur fossil fuel in a cogeneration system. This process showed an important role in terms of AD, GW and OD due to the use of non-renewable fuel as well as the associated fossil CO_2 emissions. According to this result, it was proposed three alternative scenarios (Fig. 9) with a reduction of 5% (ScC2) and 10% (ScC3) in this energy requirement (sensitivity analysis) as well as shifting from fossil fuel to wood chips as fuel in the cogeneration system in order to promote the use of bioenergy (ScC4). Fig. 9 shows the comparative environmental profile among these four scenarios although only light reductions can be achieved specifically in terms of AD, GW and OD (1% and 2% for ScC2 and ScC3, respectively). On the contrary, just as expected, ScC4 improves the environmental profile of box production process with reduction of more than 20% in categories such as AD, GW and OD mainly due to the reduction of fossil fuel consumption (33% of total contributions) as well as fossil CO_2 and CH_4 emissions (18% and 13% of total, respectively).

4.2.4 Multifunctional design of wood-based box

According to the results from eco-briefing, eco-design strategies should increase the functionality of the box, taking into account the content protection, making the storage and distribution of the product easier and showing the product in an appealing manner to the purchaser. The reuse of the wood boxes by users to store different types of products is common(e.g. toolbox and bird nest). The increase of the box functionality translates into a more intensive use, a longer life span and a consistent reduction in its environmental profile due to its use. An example that shows the multifunctional use of the wooden boxes would be their use as bird nests (Fig. 10) after introducing considerable diameter holes in order to allow bird access.

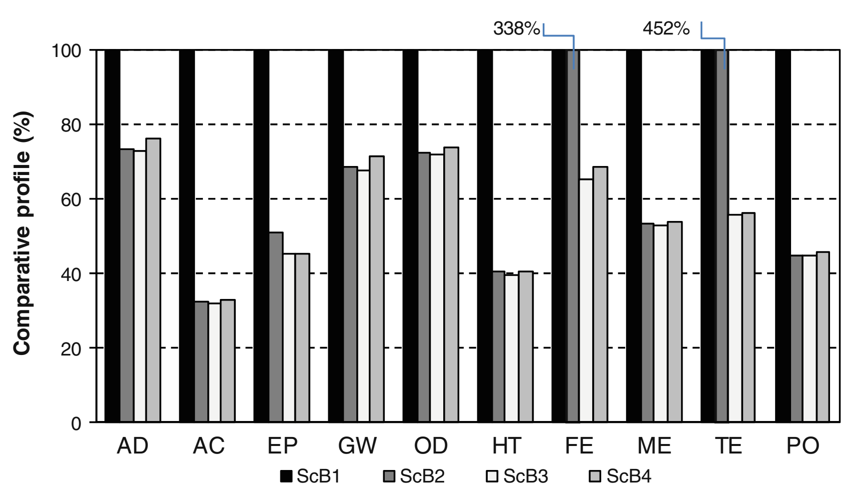

Fig. 8 Relative environmental profile of the different alternative scenarios proposed for the jute rope, the current scenario serving as the baseline (Index=100). Acronyms: *ScB1* current scenario, *ScB2* cotton from South Spain, *ScB3* hemp from East Spain, *ScB4* synthetic fibres from Central Spain

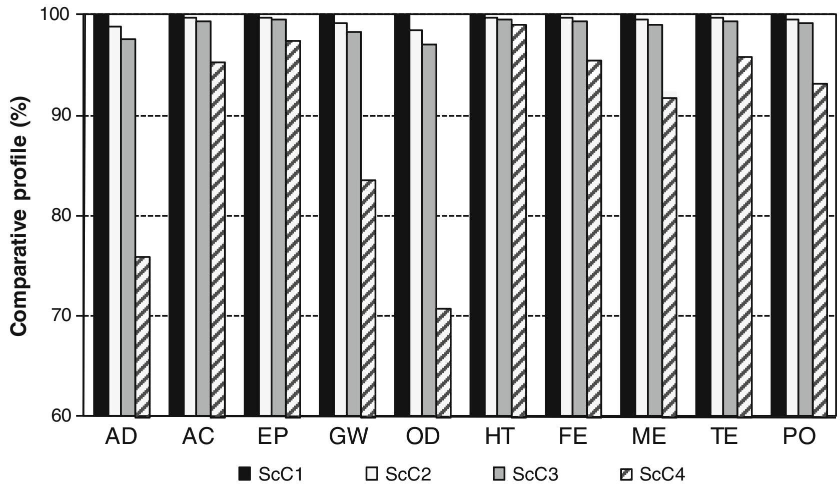

Fig. 9 Relative environmental profile of the different alternative scenarios based on energy demand, the current scenario serving as the baseline (Index=100). Acronyms: *ScC1* current scenario, *ScC2* −5% of energy demand, *ScC3* −10% of energy demand, *ScC4* bioenergy

4.2.5 Protocol of disassembling and product

The definition of a protocol of disassembling and use of the box in order to help a correct final management should be proposed since more information concerning the separation and use of the box pieces would increase the potential recycling, the reuse of components and energetic valorisation. Therefore, the environmental profile should be reduced.

5 Conclusions

This work focused on the identification and characterisation of the environmental profile of a wood box production process destined to be used in food sector for wine bottles storage. A forest-based mill considered representative of the state of the art was selected to study the process in detail. The hot spots over the life cycle of the wood box manufacturing process were identified from the inventory analysis and the impact assessment results. Three processes represent a considerably role in the environmental profile: the production of the wood-based materials (main component), the production of energy requirement in a cogeneration unit using low-sulphur fossil fuel and the transport activities related to the distribution of the handle. All these processes were significant sources of both atmospheric and waterborne emissions.

Fig. 10 Conceptual proposal of the wooden box as bird nest box (multifunctional alternative)

The implementation of DfE in the development of the wood-based box also helps to reduce its environmental impact. This article shows how eco-design applied to the development of wood box for wine bottles is valid for the delivery of environmentally friendly products, maintaining their functional and aesthetic characteristics.

We have seen that a correct methodological adaptation of the concept of eco-briefing, as a tool for communication among environmental technicians and designers, the simplification of the analytical tool used and the LCA, which facilitates the environmental analysis.

Alternative and potential scenarios were proposed and analysed in order to compare their environmental profile with the current production process. According to the environmental results, the use of bioenergy in the plant, the use of national fibres for the handle and the substitution of the MDF for alternative wood-based boards could considerable improve the environmental profile of the box. The multifunctional design of the box as well as the design of a dissembling protocol could also be considered in order to improve its environmental profile. The results obtained provide valuable information that can assist wood-based products plants to improve their environmental performance and sustainability.

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